

# Optical circuits based on Polariton Neurons in Semiconductor Microcavities

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By exploiting the polarization multistability of polaritons, we show that polarized signals can be conducted in the plane of a semiconductor microcavity along controlled channels or 'neurons'. Furthermore due to the interaction of polaritons with opposite spins it is possible to realize binary logic gates operating on the polarization degree of freedom. Multiple gates can be integrated together to form an optical circuit contained in a single semiconductor microcavity.

Owing partly to their unique spin structure [1], several recent studies have focused on the spin-dynamics [2] of exciton-polaritons in semiconductor microcavities, which operate in the strong light-matter coupling regime [3, 4]. Exciton-polaritons are part-light, part-matter quasiparticles (that represent the elementary excitations of the system) and demonstrate several qualities that make them excellent candidates for practical devices, including: a long coherence length [5]; strongly interacting nature [6]; and relative ease of excitation and detection through coupling to external light fields. Furthermore, advances in growth technology have resulted in nanostructures, which give rise to another dimension of quasiparticle control. In standard planar microcavities, methods that allow the control of propagating polariton spins have now been evidenced experimentally [7] and research has begun to focus on individual spin optoelectronic devices [8, 9]. A motivation of this field was to integrate several elements together to create all-optical circuits, however it was often not clear how such integration could be achieved.

We demonstrate a technique for making binary logic gates that act on the polarization degree of freedom of polaritons. Different logic gates can be linked together, in the plane of the microcavity, as signals can be carried along controlled channels that are created by patterning the microcavity structure such that polaritons experience a structured potential. In fact polaritons themselves do not move the whole distance from one end of the channel to the other; rather it is the switching of successive parts of the channel caused by very short propagation of polaritons that results in a long signal propagation. In this sense the channel bears a loose analogy to biological neurons, which is why we call these channels polariton neurons. Since we do not rely on single polaritons traveling the full length of the channels, the short lifetime of polaritons does not limit the length of signal propagation. The logic gates that we propose rely on the polarization multistability [10] of polaritons in microcavities.

**Polariton Neurons.** Consider a semiconductor microcavity that is patterned such that polaritons experience the potential shown in Fig. 1(b). This can be achieved by variation of the cavity width [11], applying stress [12] or putting metals on the surface of the cavity [13]. Due to the long decoherence time [14] and

the fact that in the low density limit they behave as weakly interacting bosons [15], the dynamics of polaritons can be treated in the framework of the mean-field approximation, which leads to the Gross-Pitaevskii (GP) equation [16, 17]. This equation, commonly used in the description of atomic Bose-Einstein condensate dynamics [18], has been applied to semiconductor microcavities to describe several phenomena, including: the suppression of Rayleigh scattering by impurities [17]; the spatial structure of microcavity parametric oscillator polaritons [19]; the dispersion of polariton superfluids [16, 20]; and the interference of polariton condensates [9].

Polaritons have two possible spin projections on the structure growth axis,  $\sigma = \pm 1$ , corresponding to the right ( $\sigma_+$ ) and left ( $\sigma_-$ ) circular polarizations of external photons [2]. The spin dependent GP equation is [10]:

$$i\hbar \frac{\partial \psi_\sigma}{\partial t} = \left( \hat{H}_{LP}(-i\hat{\nabla}) - \frac{i\hbar}{2\tau} + W(\mathbf{r}) \right) \psi_\sigma + \left( |\psi_\sigma|^2 + \frac{\alpha_2}{\alpha_1} |\psi_{-\sigma}|^2 \right) \psi_\sigma + p_\sigma(\mathbf{r}, t) e^{-iE_p t/\hbar}, \quad (1)$$

where the  $\sigma$  polarized internal cavity polariton field,  $\psi_\sigma$ , depends on the spatial coordinate,  $\mathbf{r}$ . The kinetic energy operator  $\hat{H}_{LP}$  represents the dispersion of polaritons. We consider only lower branch polaritons from the strong light-matter coupling - upper branch polaritons will not be excited under the conditions we propose.  $\tau$  is the polariton lifetime.  $W(\mathbf{r})$  represents a potential experienced by polaritons.  $\alpha_{1(2)}$  is the matrix element of polariton-polariton interaction in the parallel spin(antiparallel spin) configuration, respectively. It is well known that for 2D excitons and exciton-polaritons the exchange interaction strongly dominates over the direct one, and thus polariton-polariton interactions are anisotropic  $|\alpha_2| < \alpha_1$  [21]. This anisotropy strongly affects the properties of polariton systems in the superfluid regime [16, 22] and leads to remarkable nonlinear effects in polariton spin relaxation, such as self-induced Larmor precession and inversion of the linear polarization during the scattering act [2, 23]. In Eq. 1 the fields were rescaled so that only the ratio of  $\alpha_2$  to  $\alpha_1$  is significant.

The driving optical pump field is given by  $p_\sigma(\mathbf{r}, t)$  and  $E_p$  is the pump energy. If the pump energy is tuned greater than  $\hbar\sqrt{3}/\tau$  above the polariton eigen-

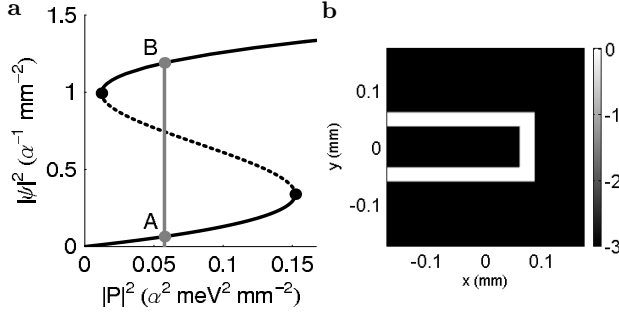


FIG. 1: a) Dependence of the intensity of a single uncoupled (spin-polarized) polariton state on pump power. The S-shaped curve is characteristic of a bistable system [24, 25, 26] and it is well-known that the middle branch (dotted part of curve) is unstable, that is, the polariton intensity can have a maximum of two possible values, A & B, for a given pump intensity. Parameters:  $E_p - E_0 = 1\text{meV}$ ,  $\tau = 3\text{ps}$ . b) Polariton potential profile in real space.

ergy (bare polariton branch energy) then for some excitation powers the system can exhibit more than one stable state [24, 25, 26]. The dependence of the polariton intensity of a single state in space can be calculated analytically [10] from the GP equation in the stationary regime, if coupling to other points in space is ignored (i.e., one assumes an infinite polariton effective mass):

$$\left[ \left( E_0 - E_p + |\psi_\sigma|^2 + \frac{\alpha_2}{\alpha_1} |\psi_{-\sigma}|^2 \right)^2 + \frac{\hbar^2}{4\tau^2} \right] |\psi_\sigma|^2 = |p_\sigma|^2, \quad (2)$$

where  $E_0$  is the bare polariton eigenenergy. If, for simplicity we consider the excitation of the system by circularly polarized light then all polaritons will have the same spin and the polariton intensity exhibits an S-shaped curve, which characterizes a bistable system [Fig. 1(a)]. If the pump intensity is increased from zero, the polariton intensity increases steadily from zero until the first turning point. For higher pump intensities, the polariton intensity jumps to the upper branch of the S-shaped curve. If the pump intensity is then decreased, the polariton intensity remains on this branch, provided the pump intensity is greater than that of the second turning point.

We solve Eq. 1 numerically (with finite effective polariton mass) to model the excitation of the system in Fig. 1(b) with a broad,  $\sigma_+$  polarized, Gaussian, cw pump. The pump is tuned above the polariton eigenenergy of the channel region and has weak intensity such that polariton intensities lie on the lower branch of the S-shaped curve. Due to the larger pump-eigenenergy detuning, hardly any polaritons are excited in the region outside the channel. We then calculate the evolution of the polariton fields after a ( $\sigma_+$  polarized) pulse is applied near one end of the channel, which locally switches the polariton intensity to the upper branch of the S-shaped curve.

The results (Fig. 2) show that after the pulse has decayed, successive regions of the channel switch to the high intensity state. This propagation of the signal continues around corners in the channel, allowing a way of creating wires for optical circuits in the microcavity plane. The switching mechanism is analogous to the optical switch-

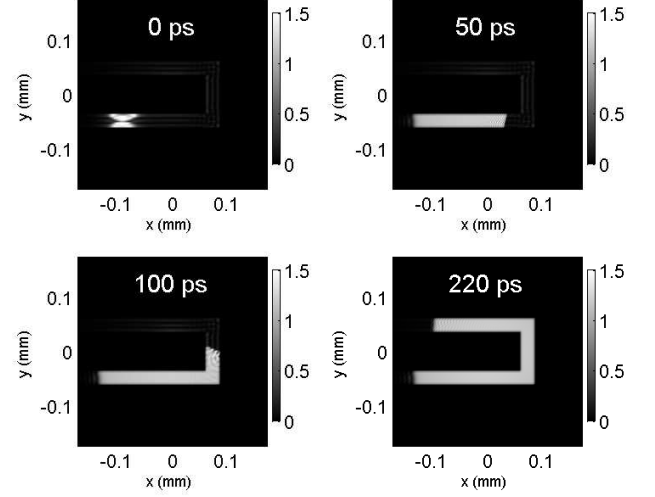


FIG. 2: Spatial polariton intensity profile at different times relative to the pulse arrival time. The polariton lifetime was  $\tau = 3\text{ps}$  and the polariton dispersion was calculated with a two oscillator model in which the exciton-photon coupling energy was  $3\text{meV}$  and the photon effective mass was  $\times 10^{-5}$  the free electron mass. Both the cw pump and pulse correspond to optical fields at normal incidence, that is, they have Gaussian distributions in reciprocal space centered at zero in-plane wavevector. The pumps are tuned  $1\text{meV}$  above the bare polariton eigenenergy.

ing waves observed in bistable semiconductor microresonators with fast electronic nonlinearity [27].

The signal propagation speed depends strongly on the intensity of the driving cw field. For our parameters it is  $1.8 \times 10^6 \text{ m/s}$ . The propagation speed could be enhanced by driving the system with a finite in-plane wavevector - however this would introduce a dependence of the signal propagation speed on the neuron in-plane direction.

**Logic Gates.** Logic gates, for creating optical circuits in the microcavity plane, can be created by exploiting the polarization degree of freedom of polaritons. When considering the polarization degree of freedom, our system demonstrates a multistability [10] rather than bistability; both the  $\sigma_+$  and  $\sigma_-$  polariton field intensities can exhibit the S-shaped curve of Fig. 1, and both can lie either on the upper or lower branch of the curve.

We now consider the merging of two polariton neurons, by restructuring the potential profile. The system is again excited by a broad but weak Gaussian cw pump, which is now elliptically polarized with a bias towards the  $\sigma_+$  polarization. The two input channels are independently excited by either  $\sigma_+$  or  $\sigma_-$  pulses. In Fig. 3 we plot the circular polarization degree in real space for the case of oppositely polarized inputs (left column) and the case of two  $\sigma_-$  inputs (right column). The circular polarization degree is defined as  $\rho_c = \frac{|\psi_+|^2 - |\psi_-|^2}{|\psi_+|^2 + |\psi_-|^2}$ .

When the signals of polariton neurons firing with opposite spin polarization overlap, we find that only the  $\sigma_+$  signal continues. This is due to the bias of the cw background field toward  $\sigma_+$  and a negative value of  $\alpha_2$ . This means that the system behaves as an OR logic gate from which the output is  $\sigma_+$  polarized if either input is

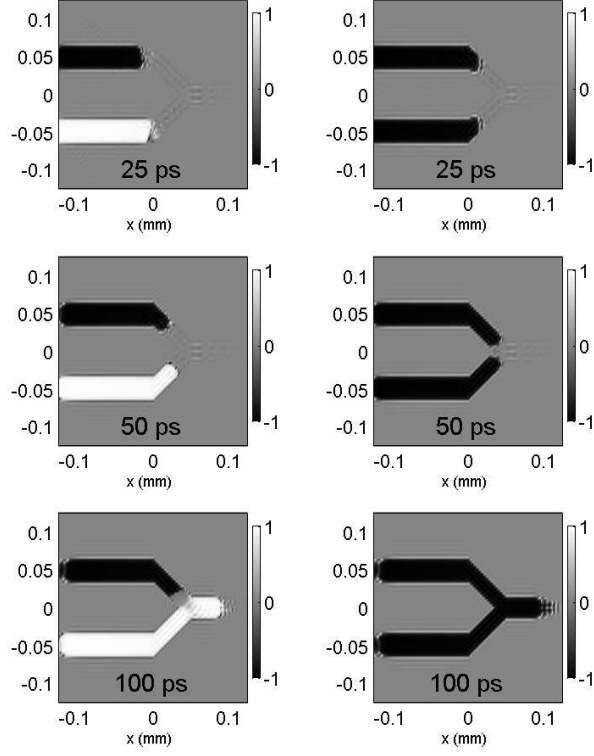


FIG. 3: Circular polarization degree,  $\rho_c$ , in a region where two polariton neurons merge, at different times relative to the pulse arrival time. In the left column the system is excited with oppositely circularly polarized pulses; in the right column it is excited with two  $\sigma_-$  polarized pulses.  $\alpha_2 = -0.5\alpha_1$ .

$\sigma_+$  polarized (alternatively we would have an AND gate if the background cw field had opposite  $\rho_c$ ).

For the parameters used in our device an uncertainty in the arrival time of pulses of at least 10ps is allowed (note that this is 10% of the device operation time). The uncertainty can be estimated as the difference in arrival time at the junction of  $\sigma_+$  and  $\sigma_-$  polarized signals when triggered simultaneously. The allowed uncertainty can be increased by adjusting the relative intensities of the cw  $\sigma_+$  and  $\sigma_-$  components (to alter the propagation speed of  $\sigma_+$  and  $\sigma_-$  signals) or by increasing the distance between the excitation points and the junction.

The power requirements of the cw optical pump would make up the majority of the power consumption of the device. We note that in Ref. 25, hysteresis was observed in GaAs based microcavities using a power of 2.8mW. In microcavities with a larger exciton-exciton interaction strength (e.g., GaN based microcavities suitable for room temperature operation) lower power requirements could be achieved. Furthermore the required pump power is sensitive to the polariton lifetime, which can be increased by using higher Q-factor cavities.

**Conclusion.** In conclusion, the short range propagation of polaritons enables the successive switching of neighboring regions along a multistable channel in space from a low intensity stable state to a high intensity stable state. This switching allows a signal to continue over distances longer than the distance a single polariton could travel before it decays (the distance is limited by the

extent of the background cw field, which must have sufficient intensity at a given point for a multistability to exist). When channels merge the polarization of the output propagating signal depends on the ingoing polarizations in a logical way, which allows the construction of binary logic gates. This gives us the opportunity to build optical circuits, in which multiple elements are integrated within a single microcavity structure.

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